

# Engine-driven Relativistic Supernovae as Sources of Ultra High Energy Cosmic Rays

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**Abstract.** Understanding the origin of the highest energy cosmic rays is a crucial step in probing new physics at energies unattainable by terrestrial accelerators. Their sources remain an enigma half a century after their discovery. They must be accelerated in the local universe as otherwise interaction with cosmic background radiations would severely deplete the flux of protons and nuclei at energies above the Greisen-Zatsepin-Kuzmin (GZK) limit. Hypernovae, nearby GRBs, AGNs and their flares have all been suggested and debated in the literature as possible sources. Type Ibc supernovae have a local sub-population with mildly relativistic ejecta which are known to be sub-energetic GRBs or X-Ray Flashes for sometime and more recently as those with radio afterglows but without detected GRB counterparts, such as SN 2009bb. In this work we measure the size-magnetic field evolution, baryon loading and energetics of SN 2009bb using its radio spectra obtained with VLA and GMRT. We show that the engine-driven SNe lie above the Hillas line and they can explain the characteristics of post-GZK UHECRs.

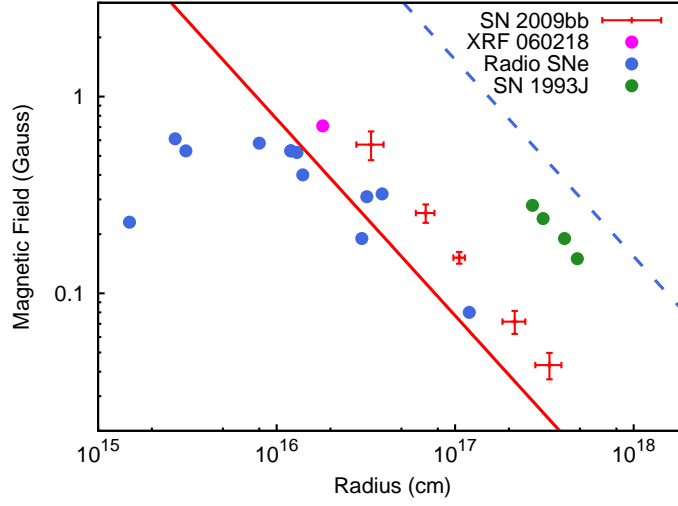
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## INTRODUCTION

Direct detection of the highest energy cosmic rays (UHECRs) by satellite-borne instruments is infeasible since these particles have such a large energy and have so a low flux[1]. They are detected[2] only by air showers[3] where the Earth's atmosphere acts as the active medium. UHECRs beyond the GZK limit[4, 5] have been invoked to propose tests of known physical laws and symmetries[6]. Understanding their origin is important for their use as probes of new physics. But the sources of UHECRs pose a problem: the magnetic rigidity of these particles are such that the magnetic fields in our galaxy are neither strong enough to contain them nor bend them sufficiently[2]. So any galactic origin would reflect the structure of the galaxy; yet among the UHECRs which have been detected until now no concentration have been found towards the Milky Way. Hence their sources are anticipated to be extragalactic. However UHECR protons at energies above 60 EeV can interact with Cosmic Microwave Background (CMB) photons via the  $\Delta$  resonance. The cross section of this process is such that only local extragalactic cosmic ray sources within 200 Mpc of the Earth can contribute significantly to the flux of UHECRs above the so called GZK limit[4, 5, 7]. Thus, to explain the 61 detected cosmic rays with energies above the GZK limit, many sources are required of the UHECRs [1]. Since particles of such high energy could not have traveled to Earth from cosmological distances, unless Lorentz invariance breaks down at these energies[6], their detection encourages the search for potential cosmic ray accelerators in the local Universe. Accordingly nearby GRBs [8, 9, 10], Hypernovae [11, 12], AGNs [1] and their flares [13], have all been suggested and debated in the literature as possible sources.

SNe with relativistic ejecta have been detected until recently, exclusively through associated Long GRBs like GRB 980425[14] or its twin GRB 031203. XRF 060218[15] associated with SN 2006aj showed that mildly relativistic SNe are hundred times less energetic but thousand times more common (in their isotropic equivalent rate, the relevant rate for UHECRs reaching the observer) than classical GRBs[15]. Radio follow up of SNe Ibc have now discovered the presence of an engine driven outflow from SN 2009bb[16], without a detected GRB. These mildly relativistic SNe, detected either using X-Ray Flashes (XRFs) or radio afterglows, a subset of SNe Ibc are far more abundant at low redshifts required for the UHECR sources, than the classical GRBs. Their mildly relativistic nature, makes them have the most favorable combination of  $\beta/\Gamma \sim 1$ , unlike both non-relativistic SNe and ultra-relativistic classical Long GRBs. In this work we (Chakraborti et al. [17] to appear in Nature Comm.), have measured the size and magnetic field of the prototypical SN 2009bb at several epochs. Such engine-driven supernovae are placed above the Hillas line and we demonstrate that they may accelerate cosmic rays beyond the GZK threshold. Together with the rates and



**FIGURE 1. Hillas Diagram:** Mildly relativistic sources ( $\beta/\Gamma \sim 1$ ) must lie above the *solid red line*, to accelerate Iron nuclei to 60 EeV by diffusive shock acceleration[18], according to  $E_z \lesssim \beta e Z B R / \Gamma$  [19]. Non-relativistic SNe ( $\beta/\Gamma \sim 0.05$ ) must lie above the *dashed blue line* to reach the same energies. Radius and magnetic field of SN 2009bb (red crosses, at 5 epochs, determined here from radio observations with VLA and GMRT assuming equipartition) and XRF 060218[15] (magenta ball) lie above the solid red line. Blue balls denote other[20] radio SNe with SSA fits. For SN 1993J only, the magnetic fields are obtained without assuming equipartition[21]. All non-relativistic SNe (blue balls) including SN 1993J (green balls) lie below the dashed blue line and are unable to produce UHECRs unlike the mildly relativistic SN 2009bb and XRF 060218 which lie above the red line.

energetics of such events, we establish that they readily explain the post-GZK UHECRs.

## MAGNETIC FIELD EVOLUTION WITH EXPANDING RADIUS

In order to derive the highest energy upto which these relativistic SNe can accelerate cosmic rays (see Figure 1), we determine the evolution of the size and the magnetic field in the blast-wave. A Synchrotron Self Absorption (SSA) model fits the initial radio spectrum of SN 2009bb rather well[16]. The low frequency turnover defining the spectral peak shifts to lower frequency with time characteristic of the expansion of the shocked region that powers the radio emission. Radii and magnetic fields can thus be measured from VLA and GMRT data at 5 epochs, for plotting on the Hillas diagram (Figure 1).

With a set of assumptions for the electron energy distribution and magnetic fields the radius of the forward shock wave at the time of the synchrotron self-absorption peak can be written as[20]

$$R \simeq 4.0 \times 10^{14} \alpha^{-1/19} \left( \frac{f}{0.5} \right)^{-1/19} \left( \frac{F_{op}}{\text{mJy}} \right)^{9/19} \left( \frac{D}{\text{Mpc}} \right)^{18/19} \left( \frac{\nu}{5 \text{ GHz}} \right)^{-1} \text{ cm}, \quad (1)$$

where  $\alpha = \epsilon_e / \epsilon_B$  is the ratio of relativistic electron energy density to magnetic energy density,  $f$  is the fraction of the spherical volume occupied by the radio emitting region,  $F_{op}$  is the observed peak flux, and  $D$  is the distance. Using the same variables, the magnetic field is given by

$$B \simeq 1.1 \alpha^{-4/19} \left( \frac{f}{0.5} \right)^{-4/19} \left( \frac{F_{op}}{\text{mJy}} \right)^{-2/19} \left( \frac{D}{\text{Mpc}} \right)^{-4/19} \left( \frac{\nu}{5 \text{ GHz}} \right) \text{ G}. \quad (2)$$

The radio spectrum of SN 2009bb at all epochs from discovery paper (Fig. 2 of ref[16]) and this work, as obtained from observations using the Very Large Array (VLA) and the Giant Metrewave Radio Telescope (GMRT), is well fit by the SSA model. Thus we can explicitly measure the size and magnetic field of a candidate accelerator, instead of indirect arguments connecting luminosity with the Poynting flux.

SN 2009bb and XRF 060218 can both confine UHECRs and accelerate them to the highest energies seen experimentally. At the time of the earliest radio observations[16] the combination of  $\beta/\Gamma \sim 1$  for SN 2009bb shows that

it could have accelerated nuclei of atomic number  $Z$  to an energy of  $\sim 6.5 \times Z$  EeV. Thus the source could have accelerated protons, Neon, and Iron nuclei to 6.4, 64 and 166 EeV respectively. Here the highest energy particles are likely to be nuclei heavier than protons, consistent with the latest results indicating an increasing average rest mass of primary UHECRs with energy[22]. Therefore, our results support the Auger collaboration's claimed preference of heavier UHECRs at the highest energies.

## RATES OF ENGINE-DRIVEN SUPERNOVAE

We require the rate of relativistic SNe to estimate whether there are enough of them to explain the target objects associated with the  $\sim 60$  detected UHECRs. SNe Ibc occur at a rate[23, 24] of  $\sim 1.7 \times 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1}$ . Their fraction which have relativistic outflows is still somewhat uncertain, estimated[16] to be around  $\sim 0.7\%$ . Hence the rate of SN 2009bb-like mildly relativistic SNe is  $\sim 1.2 \times 10^{-7} \text{ Mpc}^{-3} \text{ yr}^{-1}$ , comparable to the rate of mildly relativistic SNe detected as sub-energetic GRBs or XRFs of  $\sim 2.3 \times 10^{-7} \text{ Mpc}^{-3} \text{ yr}^{-1}$ . This leads to  $\sim 4$  (or 0.5) such objects within a distance of 200 (or 100) Mpc every year. Since SN 2009bb is still a unique object, only a systematic radio survey can establish their cosmic rate and statistical properties. However, cosmic rays of different energies have different travel delays due to deflections by magnetic fields. For a conservative mean delay[13] of  $\langle \tau_{\text{delay}} \rangle \approx 10^5$  yrs we may receive cosmic rays from any of  $4$  (or  $0.5$ )  $\times 10^5$  possible sources at any given time. Since a direct association between a detected UHECR and its source is unlikely[25], most workers have focused on the constraints[26, 27] placed on plausible sources. Our arguments above show that this new class of objects satisfy all such constraints.

Nuclei are subject to photo-disintegration by interaction with Lorentz boosted CMB photons and can travel upto a distance of  $\sim 100$  Mpc, smaller than but comparable to the GZK horizon. The local rate of mildly relativistic SNe is thus high enough to provide enough ( $\gg 60$ ) independent sources of cosmic rays above the GZK limit. The large  $\langle \tau_{\text{delay}} \rangle$  implies that it will not be possible to detect UHECRs from a known relativistic SN, such as SN 2009bb, within human timescales. However, high energy neutrinos from photo-hadron interaction at the acceleration site may be a prime focus of future attempts at detecting these sources with neutrino observatories like the IceCube.

## ENERGY INJECTION AND ENERGY BUDGET

The required energy injection rate per logarithmic interval in UHECRs[8, 28] is  $\Gamma_{\text{inj}} = (0.7 - 20) \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$ . With the volumetric rate of mildly relativistic SNe in the local universe, if all UHECR energy injection is provided by local mildly relativistic SNe, then each of them has to put in around  $E_{\text{SN}} = (0.3 - 9) \times 10^{51} \text{ ergs}$ . This is comparable to the kinetic energy in even a normal SN and can easily be supplied by a collapsar model[29]. The mildly relativistic outflow of SN 2009bb is in nearly free expansion for  $\sim 1$  year. Our measurements of this expansion show [17] that this relativistic outflow, without a detected GRB, is significantly baryon loaded and the energy carried by the relativistic baryons is  $E_{\text{Baryons}} \gtrsim 3.3 \times 10^{51} \text{ ergs}$ .

The nearly free expansion of SN 2009bb[17] can only be explained if the mass of the relativistic ejecta is still much larger than the swept up mass. Using the equations for collisional slowdown of the ejecta, from Piran [30] and integrating them numerically (see Chakraborti and Ray [31] for an analytic solution) from  $\gamma_1$  to  $\gamma_2$ , the Lorentz factors at days 20 and 222 post explosion and substituting for the progenitor mass loss rate[16], we solve for the ejecta mass to get  $M_0 \gtrsim 1.4 \times 10^{-3} M_{\odot}$ . Most of the mass in the relativistic outflow is due to baryons. The energy associated with these relativistic protons and nuclei is found to be  $E_{\text{Baryons}} \gtrsim 3.3 \times 10^{51} \text{ ergs}$ . If  $E_{\text{Baryons}}$  is distributed equally over 10 decades in energy, it can account for  $\sim 0.33 \times 10^{51} \text{ ergs}$  in UHECRs per logarithmic energy interval. With the rate of relativistic SNe in the local universe, this is consistent with the volumetric energy injection rate for UHECRs.

## DISCUSSION

The arrival directions of the Auger events have been claimed to correlate well with the locations of nearby AGNs[1]; this suggests that they come from either AGNs or objects with similar spatial distribution as AGNs. The correlation appears weaker in subsequent data[32] and the HiRes events[33] do not show such a correlation. On the other hand, UHECRs correlate well[34] with the locations of neutral hydrogen (HI) rich galaxies from the HI Parkes All Sky Survey (HIPASS). SNe Ibc occur mostly in gas rich star forming spirals. In particular the 21 cm flux of NGC3278

(hosting SN 2009bb) obtained from the HyperLeda database[35] amounts to  $\sim 1.9 \times 10^9 M_{\odot}$  of HI. Hence, the observed correlation of UHECR arrival directions with HI selected galaxies[34] is consistent with our hypothesis.

We have shown that the newly found subset of nearby SNe Ibc, with engine-driven mildly relativistic outflows detected as sub-energetic GRBs, XRFs or solely via their strong radio emission, can be a source of UHECRs with energies beyond the GZK limit. Our study demonstrates for the first time, a new class of objects, which satisfy the constraints which any proposed accelerator of UHECRs has to satisfy.

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